IX. Integration and Test Plan

Background
The conceptual SAFIR integration and test program is modeled after the JWST program. This plan, while still in development, is the best available for a similar telescope. It appears to be of comparable scale, cost, and difficulty. At this writing, JWST is in Phase B, which means that not all the decisions have been made, and the costs are still uncertain, but the general outline has been thoroughly reviewed. In the following sections, we will first summarize the major differences between the test requirements of the two observatories, and then outline the JWST concept, process, and logistics that govern the cost and schedule.

SAFIR vs. JWST – optical requirements
The SAFIR operates at approximately 20 times longer wavelengths than JWST, and all mechanical and optical tolerances are correspondingly looser. The telescope configuration will be similar unless radically different mirror technologies, such as stretched membranes, are chosen. The main implication of looser requirements is that different materials and technologies can be used, and that different test equipment capable of measuring much larger distortions is required. Standard optical tests familiar to telescope builders can in principle be implemented by using longer wavelength illumination. There are lasers that work at selected wavelengths throughout the mid and far infrared, but imaging array detectors to work with them are not common. The SAFIR flight instrument detectors will be available but only late in the program, and they will require extremely dark and cold conditions for operations.

Hence, it is likely that visible and near IR wavelength test equipment will be the standard tools. Fortunately, there are available techniques that enable wide dynamic range. These include speckle interferometry and speckle photography, which can work on rough surfaces as well as smooth ones (ref: Babak N. Saif thesis, "Simultaneous Phase-Shifted Speckle Interferometer," University of Arizona, 2004, and JWST reports). There are also laser techniques using simultaneous operation at two closely spaced optical frequencies, producing a synthetic frequency that is the difference of the two. As the field optical metrology is very important to other parts of industry, we expect a rich variety of commercial tools to suit our needs.

There is one important design implication of such a decision. The SAFIR mirror surfaces would have to be good reflectors at the test wavelengths, and would not be as rough as the loose scientific requirements would allow them to be. However, this choice may already be required by the fine guidance system, if the SAFIR uses a sensor in the focal plane of the main telescope to lock onto near IR guide stars. This configuration has the advantage that it avoids alignment instabilities between star trackers and the instrument package. If this could not be done, there would be serious implications for the integration and test program, which would have to verify such stability. We assume for this section that the SAFIR will use near IR guide stars and focal plane sensors.

Another implication of long wavelengths is that a major step for the JWST mirror testing might be deleted. The JWST mirror segments distort on cooling, so they must be measured cold, warmed up again, and polished to correct the cooling distortion. The SAFIR mirror segments might well not require this step, reducing the cost dramatically.

A further implication of the longer test wavelengths is that a full-aperture, end-to-end autocollimation test or external collimation test becomes feasible. Neither was implemented for the Hubble Space Telescope, with well-known results. For JWST, the cost of a full-aperture collimator or flat mirror was prohibitive, if indeed one could be built at all for operation inside the cold test chamber. Instead, JWST will use simultaneous center-of-curvature tests for the primary mirror, and a sampled aperture autocollimation end-to-end test. However, for SAFIR, the relaxed optical requirements mean that either a full-aperture autocollimator or a complete separate collimator might be feasible. Even so, a monolithic collimator or autocollimator is not expected to be feasible, but a segmented system would certainly be possible. In a more radical suggestion, perhaps a liquid flat mirror could be used, depending on the required test temperature. It might also be possible to use the center-of-curvature test for the primary mirror without a full-beam end-to-end test. However, considering the size of the program, and the degree to which it differs from all prior experience, it is likely that SAFIR will be required to have an end-to-end test.

An obvious difference between SAFIR and JWST is that the SAFIR telescope would be much larger. This means a different mechanical structure, a different deployment method, and may mean that a different test chamber is required. We return later to the choice of test chamber.

SAFIR vs. JWST – Fine Guidance

The JWST requires a fine steering mirror to compensate for pointing drifts, without requiring a high bandwidth servo control of the entire telescope. The need arises because the telescope structure is much less rigid than, for example, the HST structure, while the pointing requirement is quite similar. On the other hand, the SAFIR has much relaxed requirements, and might not require a fine steering mirror. In any case, the fine guidance sensor and closed-loop control will have to be demonstrated in the test chamber.

SAFIR vs. JWST – Wavefront Sensing

The ability to sense wavefront errors and correct them is critical for both SAFIR and JWST. As noted, the SAFIR wavelengths are longer, so the mechanical requirements are much relaxed. The lower operational temperatures reduce all the coefficients of thermal expansion, and the temperature gradients are much smaller as well, so that thermally induced instabilities are expected to be orders of magnitude less important than for JWST. This implies that once the SAFIR mirrors are adjusted to position, they will stay there and not require frequent adjustment throughout the mission.

It is likely that the methods used in flight (or on the ground) to determine wavefront error will be similar to those for JWST. This method is based on taking images of a point source as the focus is swept through the optimum. The complex diffraction patterns in these images carry the needed information for the Gerchberg-Saxton least-squares fitting program to determine the wavefront errors. This method was developed and proven for the HST repair mission, and has been thoroughly tested for the JWST. For coarse alignment, the JWST may also use a form of the Shack-Hartman wavefront tilt sensor, and a form of dispersed fringe sensor. All of these are optical methods that could function effectively at mid and far IR wavelengths, and there are available bright natural sources in the sky.

Given the diffraction limit of SAFIR it may be possible to bypass the JWST fine phasing (phase retrieval) altogether and go with a more accurate dispersed fringe sensor (with a goal of 1-5 µm RMS tip/tilt/piston between segments) for WFSC. This is approximately the accuracy expected for the JWST coarse sensors and might be good enough. Algorithm development would be required to take full advantage of this strategy. In principle a sufficient algorithm will reveal errors in the positions and shapes of all the optical components.

In the ground test program, the selected methods will have to be implemented in a simulator. If a full-aperture separate collimator is chosen, then all of these wavefront sensing methods can be demonstrated directly, but the separate collimator must also be characterized. If not, and an autocollimator test is chosen, then some errors can still be sensed, while some others are undetectable. In that case additional test equipment would be needed, as for JWST.

SAFIR vs. JWST – thermal

The SAFIR telescope will operate at a much lower temperature than JWST, about 4 K versus 40 K, and the detectors will be much colder, well below 1 K. A critically important trade study will be required to answer the following question: can the SAFIR telescope be tested adequately at the JWST (or higher) test temperatures? This would open up a new path through the test program and could save major resources. In principle the subsystems could be tested at their proper operating temperatures, and the full system tests would be carried out at a more convenient temperature.

The biggest thermal challenge for SAFIR will be the combined active and passive cooling of mirrors. In addition to a scaled model test of the full system (including sunshield), we recommend testing all active/passive combinations on the ground (for example cooler, mirror segments) individually before installation.

Assuming that a full-scale test of the system is required at the flight operating temperatures, a more thoroughly cooled test chamber is required than for JWST. The JWST test will have both nitrogen and helium cooled shrouds already, but the JWST support structure stands on (or passes through) the bottom of the test chamber and is anchored to room temperature. The thermal design to keep the telescope colder for SAFIR will require additional stages of isolation and active cooling. Tougher challenges lie in the fact that some of the test equipment must be warm inside the chamber. The vibration isolators must be warm, as must the interferometers. No new technology is required – extremely massive structures are already cooled to liquid helium temperatures for many other purposes, such as superconducting magnets for power generation or for particle accelerators. However, this new cooling will be expensive and the cooling process will probably take longer than for JWST.

Second, additional stages of radiation baffles will be required. These are already needed to permit the needed telescope cooling. These baffles will be built in stages to isolate the warm portions of the SAFIR from the cold portions. Otherwise, heat from the warm electronics boxes, for instance, will shine directly on the cold telescope. The assembly and test of these baffles will take longer than for JWST, but again, no new technology is required.

As for JWST, it is not likely that a full-scale thermal test of the main sunshield can be performed. It is traditional to substitute scale model tests and detailed modeling for this test, and experience says that a shield design with orders of magnitude of radiative performance margin is not hard to design. For the JWST, the calculated radiant heat reaching the telescope through the sunshield is measured in milliwatts, while the incident solar heat is hundreds of kilowatts. This degree of performance is obtained with multiple layers, and the use of more layers provides more margin.

Another part of the thermal test program is the active cooler lifetime and performance test. This test is required long before the final integration and test program happens, and is relatively inexpensive, but must be started very early in the program.

SAFIR vs. JWST – contamination during I&T

The SAFIR and JWST are both susceptible to contamination by molecules and dust, but the quantitative effects are quite different. While not much detail is known about the contamination of far IR optics by particular molecules, it is known in general that unless a contaminant film is quite thick, it does not absorb much. Indeed, it is very difficult to make a coating that absorbs far IR efficiently. In addition, most contaminant molecules are not very active in the mid and far IR, as their dipole moments are small, and in solid form they can not rotate. Hence, the allowed molecular contamination layers are relatively thick. This topic will be a good subject for detailed systems engineering, but is not expected to be a difficult problem.

The dust contamination issue is also much easier for mid and far IR radiation. Typical dust particles are much smaller than the mid or far IR wavelength, and theoretical scattering cross sections scale as an even power of wavelength. Hence, dust contamination is not expected to be a serious problem either. This is a major difference from JWST, which is quite susceptible to dust contamination. Typical ground-based telescopes have 1 to 2 % of the mirrors covered by dust. If JWST is this dusty, then the light of the Milky Way Galaxy scattering from the dust can be of the same order of magnitude as light from the interplanetary dust (zodiacal light). Hence, major effort will be expended to keep the JWST clean before and after launch.

However, the molecular contamination problem for SAFIR is still interesting, because the SAFIR optics are cold enough to condense all molecules and atoms except helium. The baseline design concept for JWST is that all the sources of such molecules are on the warm side of the sun shield, and the same is required for SAFIR. Since almost all contaminant molecules move in straight lines away from the spacecraft, there is no geometrical path for molecules from the warm sections to reach the telescope. In addition, the cooling sequence must be designed so that susceptible surfaces are kept warm longer than potential sources of molecules. The molecular contamination issue has not so far had major effects on the JWST test program except for requirements on cooling sequence.

SAFIR vs. JWST – Mechanical

The test program for the SAFIR mechanical systems will be similar to those for JWST, but as noted above, the stability requirements are much relaxed, by a factor of about 20 in motion. As the coefficients of thermal expansion are about 20 times smaller, the temperature gradients are about 10 times smaller, and the requirements are 20 times looser, the stability problem is about 4000 times easier.

This argument does not apply if it is necessary to provide stability between warm parts of the observatory and cold parts. The structure that connects them is necessarily flexible, to provide thermal isolation. If the design requires stable metrology between cold and warm parts, then this will require a (difficult) test program.

The SAFIR mechanical system is not required to be as stable as that for JWST, so it is likely that the engineering trades will lead to much lighter and much less stiff structures, with significantly more sag under 1 g. On the other hand, the driving JWST mechanical requirements turn out to be launch survival, both strength and mode frequency. With more flexible structures, launch locks for protection may be a good solution. This will clearly be an interesting challenge, but is well within the range of standard engineering process. It is likely that some new materials will become available, and they will require some characterization tests.

Deployment tests will clearly be different, since the desired larger mirror will have to be folded in a different way.

Vibration isolation tests will be part of the mechanical test program. While the JWST is expected to test a particular cooler and vibration isolation configuration, the SAFIR one will be different. The technology might be similar, since the SAFIR project could save effort by building on success.

SAFIR vs. JWST – Electrical

The SAFIR has one major electrical difference from the JWST: the detectors are likely to use a quite different technology. At long wavelengths ($\lambda > 180\ \mu m$) the best candidates are likely to use superconducting technology with very low impedances. At shorter wavelengths, high impedance photoconductor arrays would require completely different electronics. In either case, exquisitely low noise levels and cable heat flow issues imply cryogenic amplifiers near the detectors. It would greatly reduce the integration and test difficulty, and increase the odds of success, if all the detectors can be operated with their own integrated cryogenic amplifiers and multiplexers and digitizers. These do not yet exist, but are expected to be feasible, with about the same TRL as the detector systems. They should be developed together.

SAFIR vs. JWST - Space Assembly and Test

JWST is not designed for space assembly and test, and will not be accessible for repair with current technology. SAFIR could however be designed with remote assembly in mind, for example by astronauts and robots. Such remote capabilities would have to be based on a well-tested technology, developed for other missions, and are not required for SAFIR. SAFIR is small enough that a full ground end-to-end test is feasible and therefore necessary, although it does demand the largest available test chambers. In any case, a system design with modular subsystems and simple assembly interfaces and processes would be compatible with and could enhance a ground-based assembly and test program. In section XIV, we address possible enabling roles for human and robotic agents for a large far-infrared space telescope with goals that reach well beyond the baseline SAFIR.

JWST Baseline for Comparison: Hierarchical Test Program

The JWST integration and test program is structured in a hierarchical fashion. Each major subsystem must be completed, calibrated, and space qualified before delivery for the next stage of integration. For instance, each of the JWST instruments will be completed and tested as though it could never be tested again at full performance levels. That means that each one requires a full interface simulator, with optical, electrical, mechanical, thermal, and software simulations included. This approach is required for such a large and complex program with contributions from sources located in different countries. The cost of these simulators is quite significant, but there seems to be no serious alternative when the program is dispersed. It has the benefit that parallel activity is feasible; when problems are found in one area, work can continue in the others. It still carries the hazard that full integration late in the program may turn up serious interface compatibility issues. This is managed by building pathfinder equipment and test units that verify interfaces, environmental survival, and so forth. It also carries that hazard that certain performance characteristics of the full-up observatory can not be verified, because the necessary environment and test equipment do not exist. Therefore, the test program includes functional tests to verify that the subsystems are still alive and working, and have not been damaged in transport and assembly.

The JWST instrument package is to be assembled and qualified as a unit, and then delivered to the observatory. Indeed, the instrument package is called the Integrated Science Instrument Module, a name that comes from the early design concepts when it was thought possible to actually build it as an integrated system. Such a concept would have required a feat of social, budgetary, legal, and management engineering, but it was at TRL 1, i.e. wishful thinking.

JWST Baseline for Comparison: Mechanical Distortion and Sag

The JWST design process has revealed that managing the mechanical distortion is a major issue. The sag under 1 g of the JWST mirror structure would be about 1 mm, an immense amount for optical systems. This means that some mechanical mode frequencies are as low as ~ 16 Hz, since the sag is mg/k, while $(2\ \pi f)^2 = k/m$, where g = the acceleration of gravity, f is the mode frequency, k is the spring constant, and m is the mass. Even with balance to a part in a thousand, the sag would still be 1 µm. Hence, gravity compensation and recovery from launch, are difficult matters. Moreover, differential contraction of the multiple construction materials must be managed. The observatory shrinks several mm on cooling, and is made of mixed materials. The engineering solution includes passive stability and kinematic mounts, but also requires adjustable pickoff mirrors to direct the incoming beams into the instruments, and individually adjustable focus for some of the instruments, as well as adjustments on all the primary mirror segments and the secondary mirror. In other words, there is no possibility of a mechanical design that does not require actuators. Therefore, the test program must be designed to verify function and range of the actuators, and to verify that there are ways to determine what adjustments to make.

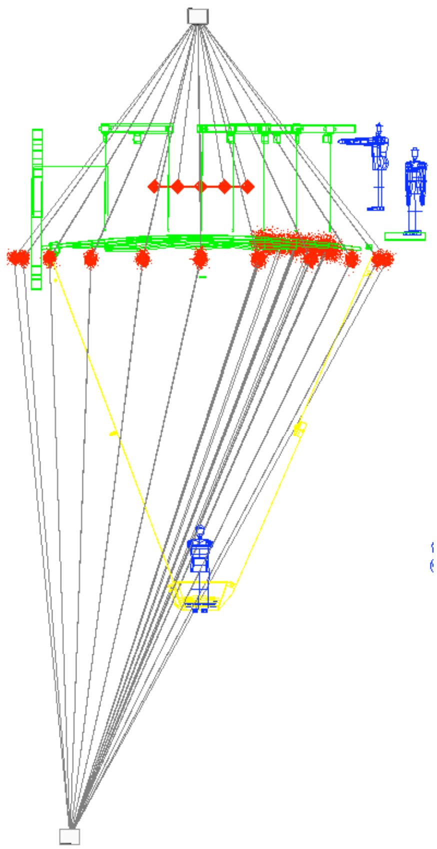


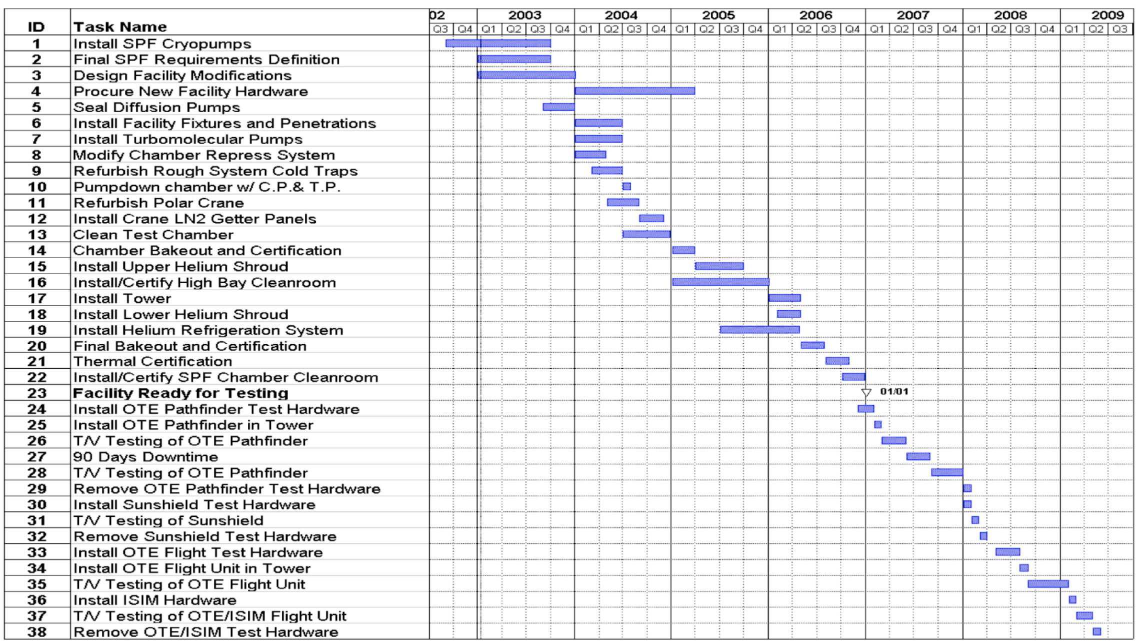
Figure IX-1: JWST primary mirror assembly and initial alignment with metrology balls and laser ranging.

JWST Baseline for Comparison: Telescope Assembly at Room Temperature

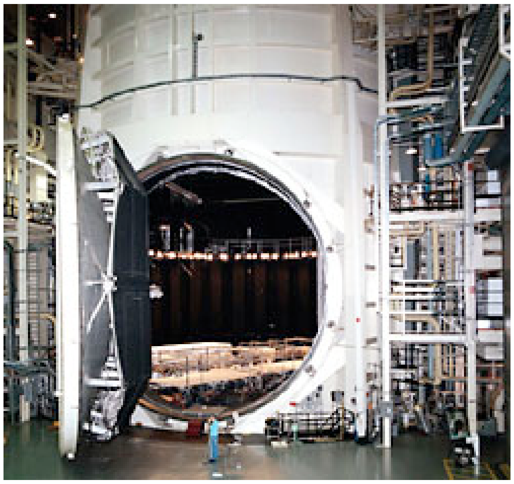
The JWST telescope is currently planned for assembly in the giant clean room at Goddard Space Flight Center, in Building 29. The previous plan to assemble it at Northrop Grumman in Redondo Beach, California had to be abandoned because the necessary height was not available in the clean rooms. Optical tests and metrology of the completed telescope will be done here for the first time. However, the optical parts will have significantly different shapes at room temperature than at operating temperatures, so the test program will have to account for that. End-to-end tests of image quality could in principle be made, but the main reason to make them is to confirm that all systems are functional and properly assembled. The cold test in vacuum is necessary for a direct demonstration of performance. On the other hand, the SAFIR telescope might well be testable at room temperature if it can be proven that it will not distort too much on cooling.

JWST Baseline for Comparison: Test Chamber

The JWST full integration test is planned for the largest usable chamber, which turns out to be the Chamber A at Johnson Spaceflight Center. This chamber is in frequent use even though it is old enough to be on the Historic Register. It is 15 m in diameter and 28 m long. An even larger chamber, 30 m in diameter and 37 m high, is located at Plum Brook, part of the Glenn Research Center in Ohio, but the trip from the airport where the observatory would land in a C5A aircraft has too many obstacles over the trip of roughly 50 miles. If SAFIR needs this chamber, it is currently available, but we would have to find a new way to get from the airport to the chamber. Given time and planning, a new landing strip could be constructed near the chamber. Alternatively, the telescope could be dismantled for shipping in smaller containers. While feasible, this approach loses many of the advantages of testing the configuration that will fly. The relaxed mechanical requirements for SAFIR may make this acceptable. Shown in the table below is a conceptual schedule for preparing and using the Plum Brook chamber for JWST. SAFIR would need additional levels of shields and coolers, and larger working volumes, but a schedule plan for SAFIR would look similar.



There are a number of other commercial test chambers, at the major aerospace firms and at Arnold Engineering in Tennessee. None to our knowledge are nearly as large as Plum Brook. However, we assume that a proper test plan will be a selection criterion for the choice of the prime contractor for the SAFIR, and the bidders will have to demonstrate that their selected test chambers are adequate. Chamber A at JSC is shown in the pictures below.



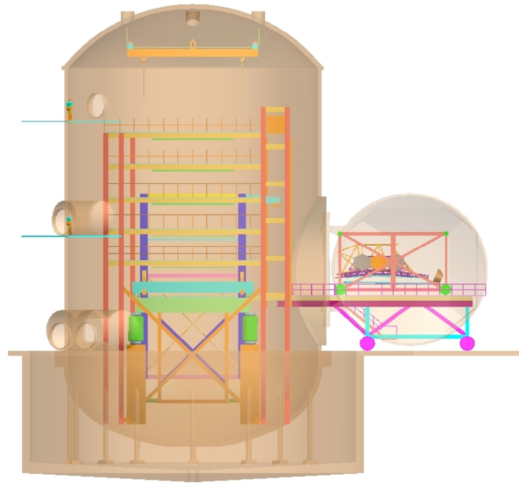


Figure IX-2: In the picture at left, the scale can be appreciated by noting the human being by the door. The diagram at right shows how, with a telescope like JWST and SAFIR, testing would require access to the chamber at a number of levels. This requires that a scaffolding arrangement be built inside the chamber.

JWST Baseline for Comparison: Optical Tests

The JSC test chamber enables an optical test with the optical axis vertical, and the telescope at the top looking down (for cleanliness and safety reasons). There is a huge steel or aluminum support tower to be built inside the chamber, capable of holding the entire optical system and test hardware. As a result the height must be substantially greater than the radius of curvature of the primary mirror. The steel support tower includes thermal isolation and vibration isolation from the ground, a major accomplishment for a structure weighing many tons.

JWST Baseline for Comparison: Primary Mirror

The initial setup of the primary mirror segments is done with metrology systems, e.g. laser ranging to reference marks on the mirrors. The next step is done with a standard optical test at the center of curvature of the primary. This equipment, with null correctors and interferometers, verifies that the entire primary mirror is correctly aligned and phased. The primary mirror for JWST has a very short focal length, so the difference between a sphere and a paraboloid is large. However, this is a standard problem and is well understood in the optical industry.

JWST Baseline for Comparison: Secondary Mirror

The secondary mirror turns out to be particularly difficult to test, because it is convex. A standard optical test would combine it with a large concave spherical mirror. However, this has two challenges. First, the spherical mirror is very large, and would need to be cooled to a low temperature to verify the secondary mirror at its operating conditions. Second, there must be a hole in the middle of the sphere to allow the beam through, and unless the sphere is very large this prevents test of a large fraction of the secondary mirror. In consequence, very different and elaborate configurations must be explored, for instance using a concave reference surface that can be measured well and compared with the secondary surface. For the SAFIR this test will be much easier, because the surface accuracy specification is relaxed compared to JWST.

JWST Baseline for Comparison: End-to-End Autocollimation Test

The main end-to-end optical test is an autocollimation test. A light source somewhere in the instrument chamber at a focal plane sends light out through the telescope. It bounces off a flat mirror and back into the instrument package, where it is analyzed. The autocollimation test verifies end-to-end function and accuracy. It has to be carefully analyzed, because there are some optical aberrations (with particular symmetries) that cannot be detected with autocollimation alone.

For the JWST test, the flat mirror cannot be obtained at a reasonable cost. As a substitute, 6 smaller flats will be used, each one centered under the junction of 3 primary mirror segments. These 6 flats are independently adjusted to match each other with a reasonable accuracy, but according to analysis they need not be perfectly coplanar. Their adjustments are correlated with those of the 6 groups of 3 primary mirror segments. The autocollimation test confirms the ability of the instrumentation and software to analyze and set the mirror segment positions and tilts, but only in certain combinations. It is currently thought that this is a sufficiently rigorous test, when combined with the center-of-curvature test of the primary mirror.

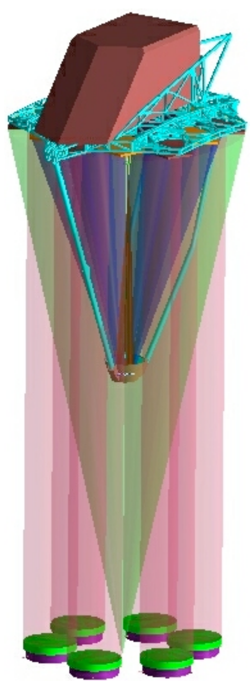


Figure IX-3: JWST Autocollimation Test Configuration. Simultaneous full aperture center-of-curvature test and sampled autocollimation. NIRCam (JWST primary wavefront sensor) also functions when cold.

JWST Baseline for Comparison: Alignment Stability and Adjustment Tests

The JWST is probably not dimensionally stable enough to be properly adjusted at room temperature in air. Experience on other programs, and with our own wavefront control demonstrations, shows that thermally induced dimensional shifts can ruin the alignment quite quickly. However, in vacuum at the required operating temperature, environmental disturbances will be much less than in air. It is not yet known how long it will take for the JWST to become dimensionally stable in the test chamber, though thermal modeling has been initiated. As noted, the SAFIR is expected to be much easier to stabilize once it reaches its operating temperature. If analysis and tests of models can prove this to be true, then the justification for a full end-to-end optical test program at flight operational temperature might be removed.

The JWST includes a Fine Steering Mirror (FSM) with a range of motion of about 1 arcsec. This is used to correct rigid-body motions of the telescope pointing on a short time scale, based on measurements from the Fine Guidance Sensor (FGS), a near IR camera in the focal plane. This system will be demonstrated in the test chamber with the end-to-end tests. The autocollimation test, even with a partially filled aperture, is capable of returning an image with a sharp point spread function (PSF) that can verify the functioning of the FGS and FSM. Depending on the stability in the test chamber, it may even be necessary for this system to be operating in closed loop to even test the JWST optics on the ground.

I&T Summary

We expect that the JWST and SAFIR integration and test programs will be very similar in scope and complexity. Almost all the same functions must be performed in both. The main differences concern the relaxed optical accuracy and mechanical stability requirements, the need for additional cooling, and the larger dimensions of the telescope. These differences may imply that the Plum Brook test chamber is the only one currently available, or alternatively that a very careful design of cooling shrouds and support structures could enable a test in the JSC chamber. It is beyond the scope of this study to answer this question, and in any case would be a selection factor in the choice of the prime contractor.

We therefore estimate that the cost of the SAFIR and JWST integration and test programs will be comparable. Experience with JWST will show whether the job becomes much more difficult as it is further defined. The main determinant of cost is the number of times that a full-scale test must be done, so in either case all efforts must be made through rehearsals and smaller scale tests to ensure that no failures occur.

As a point of view, in both cases, we take Murphy's law as a guide. Space hardware has an innate ability to sense carelessness in its creators, and tests are the only way to combat this fact of nature.